Australian Government
Department of Defence
Defence Science and
Technology Organisation

Review of Fuel Cell Technologies for Military Land Vehicles

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DSTO-TN-1360

ABSTRACT

This review provides an overview of the technologies and issues relevant to the use of fuel cells on military land vehicles as a means of extending silent watch. It explains the advantages and disadvantages of specific fuel cell technologies and provides details of specific fuel cell products relevant to silent watch extension that are available now or under development. It concludes that depending on operational parameters, both proton exchange membrane and solid oxide fuel cells have the potential to be a valuable technology for silent watch extension.

RELEASE LIMITATION

Approved for public release

Published by

Land Division
DSTO Defence Science and Technology Organisation
506 Lorimer St
Fishermans Bend Victoria 3207 Australia

Telephone: 1300 333 362
Fax: (08) 7389 6567

AR-016-098
September2014

APPROVED FOR PUBLIC RELEASE

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Executive Summary

Electrical power is a significant issue facing most military land vehicle acquisition and upgrade projects. This is due to the increasing demand for electrical power caused by the growing number of electrical systems required to be installed in military land vehicles. In this context land vehicles have at least two distinct modes of operation; engine on operations and silent watch (where the engine is off but vehicle systems are powered). The mode of operation where increased power demands are the most problematic is silent watch, due to the limits of available battery technology. Fuel cells may be able to address these problems. A fuel cell is a device which uses an electrochemical reaction to convert chemical energy to electrical energy without the need of any mechanical intermediary. They typically react hydrogen with oxygen to produce electrical energy and water. Although fuel cells use many different fuels, at their core most make use of the same hydrogen and oxygen reaction to produce electricity.

Fuel cells' advantages over batteries are higher energy densities resulting in weight and space savings, and no recharge times due to their ability to be refuelled. Fuel cells' advantages over internal combustion engine auxiliary power units (ICE APUs) are their near silent operation and higher energy efficiency. Some of the disadvantages of fuel cells include the fact that they are an emerging and hence expensive technology, are slower to respond to changes to power demand than batteries and generators, and some have long start-up and shutdown times.

Fuel type is an important factor in the consideration of fuel cells as APUs. Not only does fuel type have logistical implications but if the fuel cell does not use pure hydrogen, fuel reformation must occur to convert the fuel into hydrogen and some other by-product gas, typically carbon monoxide or carbon dioxide. Whether this fuel reformation occurs internally or externally to the fuel cell is an important design decision which has significant impacts on the weight of the system, energy efficiency, operating temperatures and pressures, fuel type and the materials used in constructing the fuel cell. The three most common fuel cell technologies for APUs are Proton Exchange Membrane Fuel Cells (PEMFC), direct methanol fuel cells and Solid Oxide Fuel Cells (SOFC).

The market survey included in this report found fuel cells under development that are likely to be appropriate for use as APUs on military vehicles. It also found mature APU

fuel cells that are currently available that are not likely to be suitable, either due to the fuel they use or limited power output.

The report concludes that SOFC or PEM FC may be a valuable tool for silent watch extension in the future and that fuel cell APUs are a technology that should be closely monitored.

Contents

Acronyms and Abbreviations

APU	Auxiliary Power Unit
COTS	Commercial Off-The-Shelf
DC	Direct Current
DMFC	Direct Methanol Fuel Cell
ICE	Internal Combustion Engine
MOTS	Military Off-the-Shelf
OEM	Original Equipment Manufacturer
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell
TRL	Technical Readiness Level
V	Volts
VDC	Volts DC
W	Watts

1. Introduction

Electrical power is a significant issue facing most military land vehicle acquisition and upgrade projects. This is due to the increasing demand for electrical power caused by the growing number of electrical systems and equipment installed in modern military land vehicles. Examples of this equipment include communication radios, battle management systems, electronic sensors, or chargers for dismounted soldier equipment. Electrical power on a military land vehicle is typically achieved with the vehicle's on-board batteries, the alternator(s) which provide power when the vehicle's main engine is running, or (if fitted) an internal combustion engine (ICE) auxiliary power unit (APU) which can be run when the vehicle's main engine is off.

When considering the problem, at least two modes of vehicle operation need to be taken into account. These are engine-on and silent watch. Engine-on operations may be static (parked) or mobile (when driving) and aim to provide enough power via the alternator(s) to power all the electrical equipment and to charge the vehicle's batteries if they are flat. Silent watch is only static and involves the use of some or all of the electronic equipment, typically with the vehicle's engine switched off. Silent watch involves a trade-off between signature management, equipment use and silent watch endurance (e.g. the amount of time this mode of operation can be sustained before the vehicle batteries are fully discharged). If the batteries cannot provide sufficient silent watch endurance, the vehicle's APU or main vehicle engine must be started to generate power, which creates an additional noise signature, fuel consumption, and additional wear and maintenance requirements on the engines.

Vehicle APUs are a solution that is sometimes used when the energy storage provided by vehicle batteries is insufficient to power the vehicle systems for the required silent watch duration. They are typically used when it is inefficient to use the vehicle's main engine to produce electrical energy to power silent watch equipment or recharge the vehicle batteries. Compared to idling the main engine these ICE APUs are typically more fuel efficient, reduce maintenance costs and have the potential to reduce heat and noise signatures. However they are not an ideal solution for silent watch operations. ICE-based APUs are not quiet and equipment used to minimise their noise signature is bulky and may not be successful at lowering noise to acceptable silent watch levels.

Another solution to extend silent watch endurance is to add more batteries. This avoids the noise problem inherent in the use of APUs but again has its own problems. Adding extra batteries consumes space and weight that is often not available on the vehicles. Additionally, extra silent watch batteries will increase the time required to recharge the batteries after a silent watch task. This may negatively impact on operational effectiveness.

Fuel cells are an emerging technology for APU applications that may have a significant advantage over both ICE-based APUs and batteries for extending silent watch. Due to their near silent operation and fuel efficiency [1, 2] they may be more suitable for silent watch compared to traditional ICE-based APUs. As they utilize fuel they do not have a

recharge phase [3]. Additionally, in most vehicle applications, the fuel efficiency and energy density of fuel cells result in a weight saving compared to the batteries required to provide the same silent watch time extension [2, 4, 5]. This does not mean fuel cells will always be a preferable alternative to batteries or ICE APUs. Fuel cells have a number of disadvantages which must be considered. As with most emerging technologies, fuel cells are generally expensive. Fuel cells are less dynamic in their energy output than batteries; they are slow to respond to changes in power demand [6] (poor load following) and some have long start-up and shutdown times.

This report investigates the suitability of fuel cells as a technology solution to extend the silent watch duration of military land vehicles or for use in recharging the vehicle's batteries without starting the vehicle's main engine. It will explain the fundamentals of fuel cell technology with the aim of providing the reader with the necessary knowledge to understand the advantages and disadvantages of fuel cell APUs and the different fuel cell technologies that are relevant. It also aims to inform the reader of the relevant fuel cell companies, the capabilities and current technical readiness of their vehicle APU products and assess whether they are suitable to extend vehicle silent watch times.

In order to maintain the unclassified nature of this report, no examples of real silent watch power requirements are used in this assessment. For the purpose of analysis 1kW has been chosen as a typical silent watch electrical load. This value is based on the author's experience.

2. What are Fuel Cells?

Fuel cells are a means of electricity generation that use an electrochemical reaction which converts chemical energy into electrical energy without the need of any mechanical intermediary. This reaction typically involves the oxidation of hydrogen to produce a flow of electrons from an anode (negative electrode) to a cathode (positive electrode) i.e electricity and water as a by-product [2] as shown in Figure 1.

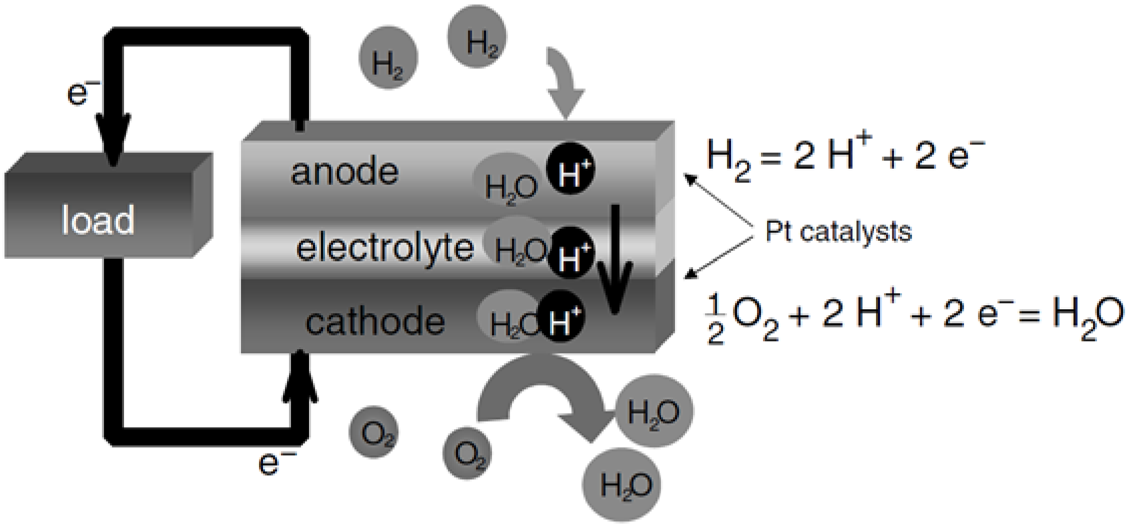

Figure 1 Operation of a generic fuel cell [2]

In order to understand the different fuel cell technologies available, it is important to be aware of the components of a fuel cell. Similar to a battery, a fuel cell includes an electrolyte sandwiched by two electrodes; an anode and cathode. The electrolyte provides a passage for ions to flow between the electrodes. Unlike a battery, a fuel cell also requires reactants (fuel and oxidiser), and exhaust extraction. Fuel flows into the anode side of the cell and an oxidiser flows into the cathode side of the cell. In simple fuel cells, the following reaction process[1] occurs: the fuel is oxidised at the anode, producing protons and electrons; the electrons cannot pass through the electrolyte and instead pass through an external circuit to produce electricity. The protons pass through the electrolyte and recombine with the electrons and the oxidant at the cathode. Depending on the nature of the fuel cell, exhaust may be produced at the anode, the cathode or in some cases both [2]. In practice, individual fuel cells are combined in series and/or parallel circuits to form a fuel cell stack to produce a desired amount of power, based on voltage or current requirements.

Generally fuel cell technologies are either referred to by the electrolyte used or the fuel consumed. This method of identifying fuel cells highlights an important point to understand when discussing fuel cell technologies. Almost all types of fuel cells use a chemical reaction which requires hydrogen to generate electricity [2, 7]. Although there are several fuel cells which run on fuel other than hydrogen (including methanol, methane, propane and diesel fuel cells), these cells usually use fuel reformation to convert the hydrocarbon fuel into hydrogen.

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1 Proton exchange membrane fuel cells (PEMFC) and direct methanol fuel cells (DMFC) follow this reaction process, while solid oxide fuel cells (SOFC) have a slightly different reaction process [1]. In SOFCs, the fuel is oxidised at the anode to produce water, carbon dioxide and electrons. The electrons pass through an external circuit and are used in the reduction of oxygen at the cathode to produce oxygen ions. These ions pass through the electrolyte and are used in the oxidation of fuel at the anode.

3. Fuelling Fuel Cells

3.1 Hydrogen

Hydrogen, either in its pure form or as reformate from another fuel is the reactant that is used, with oxygen, in almost all fuel cells to generate electricity. Using pure hydrogen, rather than reforming it from another source has a number of advantages. By using hydrogen the need for fuel reformation is eliminated, simplifying the design of the fuel cell. Eliminating the need for fuel reformation is also likely to save weight. Fuel reformation generally uses energy so eliminating it may increase the energy efficiency of the design. This is not the case in fuel cells that use by-product heat for fuel reformation (see section 4.4, Solid Oxide Fuel Cells, for an example) [2]. Additionally, when pure hydrogen is used in a fuel cell, its only exhaust is water. This is not the case when other fuels are used, where various oxides of carbon, sulphur and nitrogen are common by-products [2, 8].

Despite the advantages of using pure hydrogen there are many fuel cells that use other fuels. A significant reason for seeking alternative fuel sources are the problems inherent with storing hydrogen. Hydrogen has a very low energy density (Joules per litre) at atmospheric pressure and requires a great deal of pressurization to increase its energy density to levels comparable with other fuels [2]. This means that to store it as compressed gas, extremely strong, and hence heavy, pressure vessels must be used. Once the weight of these vessels is taken into account it is unlikely a specific energy (energy per gram) comparable with other fuels can be achieved without sacrificing energy density (Joules per litre)[2]. There is also some concern about the safety of Hydrogen. Although Hydrogen's reputation has more to do with its association with the Hindenburg disaster than fact, its reputation is still likely to be a barrier to its adoption. Compared with other common fuel gasses, hydrogen requires a much higher concentration in air for detonation and its low density makes it unlikely to build up to dangerous levels in the case of a leak [2].

One promising method for overcoming these disadvantages is the use of metal hydride storage containers [2, 8]. Metal hydride storage containers can be thought of as "hydrogen sponges" [2], where hydrogen is stored in weak chemical bonds within the container. These devices allow hydrogen to be stored at much higher densities at lower pressure than standard pressure vessels. In some cases a larger weight of hydrogen per volume is achievable than pure liquid hydrogen [2, 8]. Another advantage of these devices is that the chemical bonds that the hydrogen is stored in require a small amount of heat to be broken [2, 8], this means that in the case of a tank being ruptured, the hydrogen will be released slowly[2], which may reduce the danger of fire or explosion.

3.2 Methanol

Methanol is potentially an excellent source of hydrogen due to its high energy density (Joules per litre). Being a liquid at room temperature, it does not have the pressurisation

issues of pure hydrogen, meaning the containers it can be stored in are much lighter and its net energy density (energy density including storage medium) is much higher than both pressurised hydrogen and hydrogen stored in metal hydride cylinders as discussed in the previous section [2]. Its other advantage is its short carbon chain compared to the hydrocarbons found in other common fuels (such as petrol and diesel) which makes reformation to hydrogen a simpler process. It is even possible for some low temperature fuel cells to conduct fuel reformation within the cell (see section 3.4 and 4.3), a process that is normally only possible with high temperature fuel cells [2, 8]. Methanol does have some problems. It is extremely flammable, and does not have the existing distribution networks of more common fuels. Additionally there are significant technical challenges with reforming methanol within the cell. These will be discussed in section 4.3, direct methanol fuel cells.

3.3 Hydrocarbon fuels

This discussion of hydrocarbon fuels will focus on the broad range of common hydrocarbon fuels including petrol, diesel, LPG, methane and propane.

There are significant advantages to a fuel cell that can use a standard hydrocarbon fuel. The most significant being that standard fuels have existing distribution networks; something that is not the case for hydrogen. Additionally some of these fuels are liquid at room temperature with high flash points, making safer than hydrogen [2]. Hydrogen does not occur naturally, meaning it needs to be extracted from another chemical such as water. As such it is more appropriate to think of hydrogen as an energy storage device than as an energy source. Hydrocarbon fuels do not have this problem.

These alternative fuels do have some drawbacks, namely they need to undergo fuel reformation (see section 3.4), which may have a space, weight or energy cost. Additionally they will have more undesirable chemical by-products in their exhaust. In a best case scenario carbon-dioxide will be produced, however carbon-monoxide is also possible, and other chemicals such as oxides of sulphur and nitrogen.

3.4 Fuel Reformation

In application to fuel cells, fuel reformation is the name given to any process by which a fuel source not suitable for use by a fuel cell is converted to useable fuel. This process can either occur within the cell and is referred to as internal fuel reformation or in a dedicated fuel reformer and is called external fuel reformation [2, 8]. The most common form of fuel reformation is called steam reforming. In steam reforming, a hydrocarbon fuel is combined with water at high temperature to form hydrogen and carbon monoxide in the following chemical reaction (note that x and y will differ depending on the specific hydrocarbon being used) [2, 8].

$$C_xH_y + xH_2O \rightarrow \left(x + \frac{y}{2}\right)H_2 + xCO$$

This process can be used to reform most hydrocarbon fuels. It typically occurs at high temperature, above 500°C [2]. Consequently low operating temperature fuel cells, such as proton exchange membrane fuel cells (PEMFC), are not able to use this process internally [2, 8]. Another issue with steam reformation is the production of carbon monoxide. Carbon monoxide is attracted to the platinum based catalysts used in many fuel cells and will prevent the hydrogen fuel from reaching the catalyst [2, 8]. In fuel cells that use these catalysts, the carbon monoxide must be removed or further reformed into carbon dioxide before the fuel can enter the cell [2, 8]. For these two reasons, many fuel cells use external fuel reformation. This necessitates dedicated fuel reformation equipment, increasing system weight and complexity and decreasing energy efficiency.

A common type of fuel cell which can use internal steam reformation is the solid oxide fuel cell (SOFC). These cells operate at such a high temperature (around 800°C) that they do not require a platinum catalyst. Additionally, these cells can use the carbon monoxide produced by steam reformation as fuel and produce water as a by-product which can be used in the reformation process [2, 8]. The advantages of using internal steam reformation in SOFC will be discussed in Section 4.4.

Another commercially available fuel cell technology which uses internal fuel reformation is the direct methanol fuel cell (DMFC). Methanol is unique in that, with the use of appropriate catalysts, it can be reformed into hydrogen and carbon dioxide without producing carbon monoxide and at temperatures as low as 80°C [2, 8]. This means that it is possible to use internally reformed methanol in low temperature fuel cells that use platinum catalysts, the most common of which are PEMFC. Due to a number of technical issues PEMFC are the only commercially available DMFC, resulting in DMFC being considered a subset of PEMFC [2]. As will be discussed in Section 4, water management is a significant issue for PEMFC. As direct methanol reformation consumes water in a similar, although much more convoluted [2], reaction to steam reformation, most DMFCs require an additional water supply. This can be accomplished by using a methanol water mix as the fuel supply.

4. Fuel Cell Types and Market Survey

This section reviews and explains the types of fuel cells available and a market survey to highlight the capability and maturity of fuel cells that were available at the time of writing this report in early 2014.

4.1 Market Survey Method

The market for fuel cell vehicle APUs is a developing one. The result of this is a small sample size for this survey. For the purposes of the survey any fuel cell being marketed as being for use on vehicles, and hence most likely meeting the requirements for portability were considered. In order to give an indication of the future capability of these devices any device under development by a commercial entity as well as all COTS and MOTS devices were included in the survey. Devices under development by academic organisations

without an industry partner were not considered due to the difficulty in predicting whether they will be commercialised. Fuel cell devices for this survey were found through internet searches, by reviewing industry journals, magazines and press releases. The technical data for these devices was sourced from product data sheets and press releases and by contacting product vendors.

4.2 Proton Exchange Membrane Fuel Cells (PEMFC)

Proton exchange membrane fuel cells (PEMFC) are an important technology in the land vehicle silent watch context. The name refers to this type of fuel cell's electrolyte which is a solid polymer that hydrogen ions (protons) can pass through. PEMFC use platinum as a catalyst and, until recently, this resulted in high costs precluding use in many applications. The amount of platinum required has been significantly reduced by recent developments. A modern 1 kW fuel cell would likely contain approximately ten dollars worth of platinum [2], an insignificant fraction of the total cost of the cell.

The solid nature of the PEMFC electrolyte is a significant advantage to this type of fuel cell. A solid electrolyte removes the problem of electrolyte spillage. Additionally the electrodes can be directly coated with the electrolyte, resulting in structural stability with reduced material.

PEMFCs have a relatively low operating temperature (typically 60 to 80 °C) giving them a shorter start-up time than many other fuel cell technologies [8]. Low operating temperatures also mean that PEMFCs do not have the problems of thermal expansion and insulation which are significant design considerations in other fuel cell technologies.

Proton exchange membrane fuel cells, like most fuel cells, use hydrogen and oxygen as their reactants. Most commonly the oxygen is sourced from air. Hydrogen can either be sourced from bottled pure hydrogen or reformed internally or externally from hydrocarbon fuels as discussed in Section 3.4 .

The PEMFC uses a solid polymer electrolyte that it is hygroscopic (absorbs water) and must remain hydrated. If the electrolyte dries out, protons will no longer be able to flow. However, too much water will interfere with the flow of fuel and exhaust gasses, meaning that the correct balance of water is critical to the efficient operation of a PEMFC [2]. As water is a by-product of fuel cells it is possible for the electrolyte to be kept hydrated without an external water supply, but at higher operating temperatures (where PEMFCs are the most energy efficient), water production cannot keep up with evaporation [2]. This trade-off means that water management is a very important consideration for PEMFC designers. This has led to a number of different design solutions, some of which require a water supply to operate, some of which produce water and some others maintain water equilibrium internally.

Some examples of APU devices using PEMFCs are described in the following sections.

4.2.1 H3 350 Methanol Power System by Ser Energy

Figure 2 The H3 350[9]

The H3 350 Methanol Power System is a fully independent system which includes a PEMFC, an external fuel reformer and a rechargeable battery for power to start the fuel cell[9]. This is a mature system that currently has an application as the drive power source for small gardening/utility type vehicles and is suitable for use as an APU [9]. It has a maximum power output of 350 W [9]. 350 W is likely to be a significant percentage of silent watch power in typical vehicles but the vehicle batteries may need to provide additional power. In low load scenarios, such as cases where silent watch equipment has been pared back to essential equipment only, the fuel cell system may be able to provide 100% of silent watch power. This means that in the best case scenario in some vehicles this system could extend silent watch as long as fuel is available, however, if the fuel cell was being used to recharge the vehicles' batteries, its limited power output would result in an unacceptably long recharge time. The system weighs 13.7 kg. At peak power it uses 350 mL of fuel per hour [9].

A major disadvantage of this system is the fuel. It requires a blend of 40% de-ionized water and 60% methanol [9]. This is not a standard fuel and would impose significant logistical costs in military applications.

4.2.2 PowerPac by PowerCell

PowerCell are a manufacturer with plans to develop 2kW and 4kW systems called the PowerPac [10]. At the time of writing this report in early 2014 the PowerPac was not a mature product. PowerCell demonstrated a prototype in May of 2013 and expect production units to be available by 2015 [11]. The PowerPac will come with an integrated reformer and will run on diesel [10]. A 2 kW system is likely to provide enough power for all current silent watch needs in a typical vehicle and may be able to charge the vehicle batteries at the same time. As this is a developmental system, information is limited,

however PowerCell does have an unintegrated 2kW PEMFC which weighs 11.3 kg and has a peak output of 19 V [10]. An integrated system may be expected to include a fuel reformer, a battery for start-up and power conditioning electronics and would be significantly heavier. The main advantage of this system would be its use of diesel fuel as it would provide a significant logistical advantage over other PEMFC systems.

4.3 Direct Methanol Fuel Cells (DMFC)

Direct methanol fuel cells are a type of fuel cell that use methanol fuel without the need for an external fuel reformer. As discussed in Section 3, methanol has the potential to be an important fuel for fuel cells because of its ability to be reformed into hydrogen at low temperatures [2, 8]. This makes it the only fuel, other than pure hydrogen, that low temperature fuel cells like PEMFC can use without an external reformer. Methanol also has a much higher net energy density than hydrogen due to the issues discussed in section 3.1. Hydrogen storage techniques generally involve pressurised gas in heavy containers or hydrogen absorbing materials [2, 8]. This weight saving is offset to some extent in fuel cells that use external reformation by the weight of the fuel reformer. Hence there is a significant potential advantage to a fuel cell that can used methanol directly.

Unfortunately there are some significant technical challenges in the design of DMFC that have yet to be solved [2, 8]. The first is that internal methanol reformation is a slow reaction, resulting in low power output. The second is that methanol can pass through the proton exchange membrane, decreasing output voltage and energy efficiency [2]. This is due to methanol being highly soluble in water. These two problems mean that DMFCs are not currently suitable for applications where over 100 W of power is needed. Current research to solve these problems focuses on developing catalysts that will improve reaction rates and electrolytes that methanol cannot pass through [8].

4.3.1 Emily 2200 by SFC Energy

Figure 3 The Emily 2200 [12]

An example of a DMFC designed for military use is the SFC Emily 2200. This system is MIL-STD-810F (humidity, sand and dust, vibration and drop) compliant [12]. The Emily 2200 is a 90 W 12/24 VDC system that weighs 12.5 kg and is designed for vehicle use [12]. It is the only direct methanol APU identified by this investigation that is compliant with military specifications. However, its low power output and low power-to-weight ratio makes it unsuitable for integration with a military vehicle for the purpose of extending silent watch. This is likely due to the severe technical limitations of current DMFCs discussed in the preceding section. It is unlikely more DMFC Military Off-The-Shelf (MOTS) or Commercial Off-The-Shelf (COTS) vehicle APUs will become available until significant technological advances have been made.

4.4 Solid Oxide Fuel Cells (SOFC)

Solid oxide fuel cells are so named for the solid oxide ceramic that is used as an electrolyte. Unlike PEMFCs, SOFCs do not require the electrolyte to be hydrated. As discussed in Section 4, the hydration of the electrolyte is a significant design consideration for PEMFCs. The elimination of this need in SOFCs has the consequence that SOFCs tend to be simpler devices than PEMFCs [2]. The other major point of difference is operating temperature. Solid oxide fuel cells typically operate at an internal temperature of between 600 ^{0}C and 1000 ^{0}C [2] (noting that the external temperature of a SOFC device may not be noticeably

warmer than its surroundings). This high internal temperature is both an advantage and disadvantage of this technology which is explained as follows:

- Advantages of high operating temperatures

  The higher operating temperature means that internal reformation of fuel using steam reformation (as discussed in Section 3) is simple and efficient [2]. Thus SOFCs have the most flexible fuel requirements of any current fuel cell technology. A SOFC may be able to use one of, or a combination of diesel, JP-8, propane, methane, LPG or methanol without an external reformer. The use of diesel and JP-8 is especially advantageous as these are standard military fuels requiring no additional logistical burden in military operations.

- Disadvantages of high operating temperatures

  There are several disadvantages of operating at such high temperatures. SOFCs tend to have long start up times due to the time it takes to get the cell up to its operating temperature. As with most high temperature fuel cells, they have to be heated very carefully, as mismatches in thermal expansion could damage the cell [4]. Additionally, a large power source separate to the fuel cell is required to heat the cell during starting. This is often achieved by burning fuel or using rechargeable batteries. Both techniques add to weight and complexity of the design. The need for bulky thermal insulation to protect users, reduce heat loss and, in a tactical environment, reduce thermal signatures also contributes to space and weight costs. It appears that recent technology developments have mitigated this issue, with lightweight SOFCs with short start times (several minutes) on the verge of becoming commercially available. If these issues have been addressed, the high energy efficiency and fuel flexibility mean that SOFCs are likely to be the most appropriate fuel cell technology for a number of mobile applications. These applications include APUs to extend silent watch time.

Some exemplar devices using SOFC technology are described in the following sections.

4.4.1 Defender series by Ultra Electronics AMI

Figure 4 The D245XR (left) and the D300 (right) [13]

The Defender series consists of the D300 and D245XR fuel cells. The D300 is a 10.9 kg, 300 W system that can output 12, 14, 24 or 28 V. It is rated to MIL-STD-810F (Rain, sand and dust, shock and vibration) [14]. At 2.6 kg, the D245XR is a much lighter system and with a 245 W peak output has a much higher power to weight ratio compared to the D300 [14]. However, the D245XR has not been environmentally tested and is limited to a 28 V DC output [13] (which is preferred for military land vehicles). It is likely that at 300 W and 245 W both systems will provide a significant percentage of silent watch power in typical vehicles. In low load scenarios, such as cases where silent watch equipment has been pared back to essential equipment only, the D300 may provide 100% of silent watch power. This means that in the best case scenario in some vehicles the D300 could extend silent watch as long as fuel is available. Under typical silent watch load scenarios, the D300 would reduce the load on the batteries, and extend silent watch battery endurance. Both these products use 112 g of propane per hour from a camping stove gas cylinder [13, 14]. This may be a significant advantage over systems that use specialised fuels such as methanol and hydrogen.

4.4.2 Nordic Power

Figure 5 Nordic Power SOFC [15]

Nordic Power is developing a 1 kW, diesel-powered SOFC system designed for use as an APU in military vehicles [15]. At the time of writing, in early 2014, this is not a mature product. According to Nordic Power's website, demonstration units were expected to be shipped late 2012, however due to delays this did not occur [15]. At the time of writing the company would not give any indication when they would have a completed product. This is indicative of the state of the fuel cell APU market where many products are still in final stages of development and production delays are common.

4.4.3 PowerCore by Topsoe Fuel Cell

The Powercore is a 2 kW SOFC that can use natural gas or diesel as its fuel [16]. Topsoe appear to be an Original Equipment Manufacturer (OEM) rather than a provider of COTS systems. Their business model relies on a third party to integrate their cells into a useable system [16]. There is currently a partnership between Volvo and Topsoe that is developing an APU for use in trucks. A demonstration unit is advertised for delivery in 2014 [17]. A 2 kW system is likely to provide enough power for current typical silent watch needs with some headroom for future increases in power demands. 2 kW of power would also be suitable for recharging a vehicles' batteries in an acceptable time period (typically 2 to 6 hours depending on battery capacity and configuration).

4.4.4 Delphi Solid Oxide Fuel Cell Auxiliary Power Unit

Figure 6 The Delphi SOFC APU mounted to a truck [18]

Delphi has developed a 5 kW SOFC designed for fitting to commercial trucks. The system outputs 110 VAC or 12 VDC and can use natural gas, propane or diesel as fuel [18]. According to conversations with company representatives, Delphi is currently searching for a large enough customer to justify the cost of going into production. At 5 kW the Delphi system would provide all the silent watch power needed for most applications and may provide additional export power. Although size and weight information was not available, the system is designed for integration with large commercial trucks, which have more space and weight available than most military vehicles. It is possible that size will make this system unsuitable for many military vehicles.

4.4.5 Python by Merlin Power Systems

Merlin has developed a 1.2 kW 28 V SOFC system. It is a diesel-powered system that is designed to be integrated with a vehicle. The system is MIL-STD-810F (High/low temp, salt/fog, shock/vibration, dust/sand) certified and is rated for 2,000 hours of operation before it needs to be replaced or refurbished [19]. A 1.2 kW system is likely to provide enough power for most typical silent watch applications. The unit consumes 380 mL of fuel per hour and weighs 8.1 kg [19]. This means that by adding less than 12 kg (including extra fuel) the Merlin device could potentially increase the silent watch endurance of a vehicle by eight hours. However, this is a very new product and the claims of Merlin are yet to be demonstrated or validated. The first production units were due to be delivered in December 2012, but this was delayed due to a product defect. DSTO intended to purchase this product for evaluation but as of April 2014 no units had been delivered and DSTO cancelled its order.

4.5 Market Survey Summary

Table 1 summarises characteristics of the fuel cells identified in this survey and includes an estimated TRL based on the statements and product data sheets from the various vendors. Five fuel cells were identified as TRL 7 or above. The Emily 2200's power output is too low to have any significant impact on silent watch endurance in a typical military vehicle. The H3 350 and the Defender D300 would increase the silent watch endurance of most military vehicles; however they would not provide all the silent watch power and hence would have a significant drawback compared to most in-service ICE APUs. This leaves the Delphi and Python fuel cells. Both these fuel cells are SOFC devices that can utilise diesel fuel. This is likely to be an important factor in the adoption of fuel cells in vehicles. By utilising the vehicle's own fuel supply the system will minimise its logistics cost. The Delphi is a 5 kW unit designed for commercial trucks. Delphi does not provide size or weight information about their system but based on its power output, which is significantly above the needs of most military vehicles, it is reasonable to expect that it will be large. Additionally Delphi is not currently accepting orders for their system as they will not be going into production until they have identified a customer large enough to justify the cost. The Merlin Power Systems Python fuel cell by comparison is of an appropriate size and weight for use as a vehicle APU and outputs a suitable amount of power. The manufacturer was expecting to be shipping their first units in May 2014; however production delays mean that this target was not met.

Table 1 Market Survey Summary

Name	Type	Fuel	Maximum Power	Weight	Fuel Consumption	TRL
H3 350 [9]	PEMFC	40%water, 60% methanol	350 W	13.7 kg	350 mL/hr	8
PowerPac [10, 11]	PEMFC	Diesel	2 kW	>11.3 kg	-	6
Emily 2200 [12]	DMFC	Methanol	90 W	12.5 kg	72 mL/hr	9
Defender D300 [13, 14]	SOFC	Propane	300 W	10.9 kg	112 g/hr	8
Defender D245XR [13, 14]	SOFC	Propane	245 W	2.6 kg	112 g/hr	6
Nordic Power [15]	SOFC	Diesel	1 kW	-	-	4
PowerCore [16]	SOFC	Natural gas/ Diesel	2 kW	-	-	4
Delphi [18]	SOFC	Natural gas/ Propane/ Diesel	5 kW	-	<2 L/hr	7
Python [19]	SOFC	Diesel	1.2 kW	8.1 kg	380 mL/hr	7

5. Conclusions

Fuel cells have the potential to extend silent watch endurance in military vehicles. Recent technological advances are overcoming the problems of long start-up times, weight and size. Additionally, fuel cells that use diesel are becoming available. This is important as it eliminates the need to develop a new supply chain, which is a significant obstacle to the adoption of fuel cells which use non-military standard fuels.

SOFCs, in particular, appear to be the most promising. Their size, weight, energy efficiency and use of diesel mean that SOFC APUs can be significantly smaller and lighter than internal combustion engine APUs while using less diesel and providing enough power to sustain silent watch activities. However, as of 2014 diesel SOFC is not a proven, mature technology. The diesel SOFCs that have been demonstrated tend to have problems regarding their reliability and load following capabilities. This leads to concerns regarding the suitability of this technology that can only be assuaged by successful testing of as yet unavailable MOTS or COTS diesel SOFC APUs.

PEMFCs with external reformers allowing them to use standard fuels may also prove to be a valuable technology. They have the disadvantage of the reformer adding significant weight but their shorter start-up times may make them more suitable for use as a vehicle APU. Once again, as of 2014 these systems are not a proven, mature technology. As these systems become commercially available it will be important that they are investigated to ensure that their potential costs and benefits to military vehicles are understood.

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DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA	 1. DLM/CAVEAT (OF DOCUMENT)

2. TITLE	3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION)
Review of Fuel Cell Technologies for Military Land Vehicles	Document (U) Title (U) Abstract (U)
4. AUTHOR(S)	5. CORPORATE AUTHOR
Benjamin Campbell, Simon Crase and Brendan Sims	DSTO Defence Science and Technology Organisation PO Box 1500 Edinburgh South Australia 5111 Australia

6a. DSTO NUMBER	6b. AR NUMBER	6c. TYPE OF REPORT	7. DOCUMENT DATE
DSTO-TN-1360	AR-016-098	Technical Report	September 2014

8. FILE NUMBER	9. TASK NUMBER	10. TASK SPONSOR	11. NO. OF PAGES	12. NO. OF REFERENCES
2014/1160976/1	07/357	DSTO (AVS STC)	17	19

13. DSTO Publications Repository	14. RELEASE AUTHORITY
http://dspace.dsto.defence.gov.au/dspace/	Chief, Land Division

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111

16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CITATION IN OTHER DOCUMENTS Yes

18. DSTO RESEARCH LIBRARY THESAURUS

Fuel Cells, Vehicle Power, Silent watch

19. ABSTRACT
This review provides an overview of the technologies and issues relevant to the use of fuel cells on military land vehicles as a means of extending silent watch. It explains the advantages and disadvantages of specific fuel cell technologies and provides details of specific fuel cell products relevant to silent watch extension that are available now or under development. It concludes that depending on operational parameters, proton exchange membrane and solid oxide fuel cells have the potential to be a valuable technology for silent watch extension.